ScienceDirect
www.sciencedirect.com

Journal of Nuclear Instruments and Methods in Physics Research 00 (2021) 1–5

www.elsevier.es/RIAI

A High Voltage Distribution System for Mu2e Electron Tracker

W.Ahmed[a,1,*], Ed.Hungerford[a], A.MukeherJee[b], V.Russu[b], R.Tschirhart[b], M.Yucel[b]

[a] University of Houston, Texas, USA.
[b] Fermi National Lab, Batavia IL, USA.

Abstract

This paper describes the design, development, and testing of a High Voltage Distribution System (HVDS) which features an embedded Smart Switch (SS) which distributes high voltage (HV) from a HV supply to 6 independent straw-detector panels of the a straw-tube detector array in the Mu2e electron tracker. The HVDS not only provides, but controls, and monitors the HV in individual straw-panels. It controls for each plane, independent on-off, HV limits, current limits, filtration, channel isolation, and a Crowbar for over-current protection. Inter-communication and control is based on TCP/IP protocols through a Raspberry Pi. Tests have confirmed long term HV stability, accuracy in HV and current readout, and over-current tripping. The HVDS performance is comparable to, if not better than, commercial HV systems.

Keywords:
HVDS, Electron Tracking Detector, Mu2e, Straw Detector, CLFV, DAQ, IOC, DAC, ADC.

1. Introduction

The Mu2e experiment is a search for Charged-Lepton Favor Violation (CLFV) in a neutrino-less Muon-to-Electron conversion (Mu2e) in the field of a nucleus. If a direct Mu2e conversion occurs without neutrino emission, a mono-energetic, 105 MeV electron is emitted. This electron can be detected with a single event sensitivity of 2×10^{-17}, by tracking it's spiraling motion in a 4m long, high-resolution solenoid (RMS $\leq$ 200 keV/c) (1). Straw-Tube detectors (ST) mounted in planes, are located in the evacuated bore of a magnetic solenoid, and measure the"hit" positions of emitted electrons. When all "hits" on a track are combined, the momentum of the electron can be obtained. The tracking planes require a stable, monitored, and controlled high voltage (HV) source. Figure 1 shows a plane with combinations of six panel (top and bottom), each panel covers 1/3 of a circle so 3 panels end-to-end form a circle.(2).

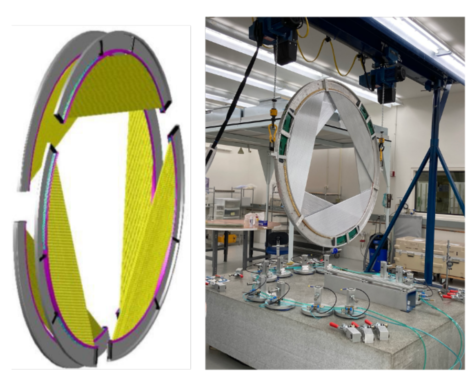

Figura 1: Six Panels are joined to make a Plane.] Right; Two planes are joined back-to-back after a 60° rotation to form a station.(see the description in the text)

2. The Straw Tracker

The Electron tracking Detector (EDT) consists of 96 straw tubes (ST) installed in 2 layers on 120° circular arcs (a panel). Each ST has a 25μm sense wire inside a 5 mm diameter ST made of 15 μm thick, metalized Mylar. An assembled plane is shown in Figure 1 - left (3)]. Planes are formed by joining 3

*Author and correspondence.
Email: waqar@cern.ch (W.Ahmed)

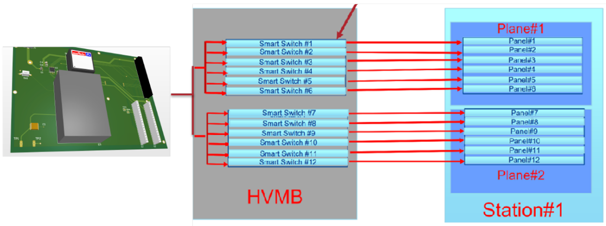

Figura 2: Mu2e High Voltage Architecture)

panels into a planar arrangement forming a 360^0 ring; Figure 1 right. Two planes are joined back-to- back with a relative 60^0 rotation to form a station, which has an inner radius of 700 mm and a varying ring width of approximately 140 mm. A station is a 12-sided figure (dodecagon) with a 380 mm central hole. There are 18 stations distributed over a 3m length in the 4m warm bore of a 1 Tesla, superconducting solenoid. The interior of the solenoid is evacuated to 10^{-14} Torr.

The ST panels require approximately 1.5 kV to be operational. The drift gas is Ar:CO^2 (80:20), and each plane has independent HV, a maximum current setting, and a crowbar system for over-current protection. A Smart Switch (SS) was designed to distribute, monitor, and control the HV through Mother Boards (HVMB) for each plane

The purchase of 36 commercial HV supplies with the addition of a distribution system would be cost prohibitive. It would also be difficult to control the distribution without additional electronics. This is particularly relevant for the Mu2E tracker, as the HV supplies must be isolated by distance and/or radiation shielding from the muon production target which is positioned just upstream of the solenoid. Also the use of long HV cables would slow the trip response due to the cable length and capacitance. However, the slow-crowbar trip problem was mitigated by separating the HV supply from the trip response control. Thus the HVMBs was placed near the planes.

3. HV Mu2e Tracker System

A nominal operating HV of 1.5 kV is applied to the straws through a HVMB module in steps of 1V. This ensures sensitive HV adjustment for each plane, and provides optimum amplification of the ionization created in the ST. Each HV panel has independent voltage on-off, current limits and monitoring (nA to μA), and over-current protection (crowbar). The HV distribution has, HV stability in the individual detector channels, over current protection, and channel ground which prevents less than a 25 V difference in voltage between the ground of a channel and the HV ground of the SS. The HV input to the HVMB system is supplied by a DC-DC converters. Figure 2 shows the architecture of the High Voltage System.

The maximum current for each station is 250 μA and the maximum voltage is 1.5 kV. The accuracy of the Voltage/current settings and monitoring were 1V and 10 nA at 250 μA, respectively.

4. Summary of the HVDS Instruments

- The Electron Tracker (ETD) consists of eighteen stations with each station contains 2 detector planes, plane contains 3 panels, and each panel contains 96 straw detectors. This gives a total of 576 (96x3x2) Straw Detectors (ST) per station.
- Each plane has independent HV input, control, filtration, and crowbar systems.
- The high voltage power supplies have active, over-voltage protection for each plane.
- A ground reference for the HV-power return is established at the panel by a connection to station ground.
- There is a HV supply and return cable for each panel.
- Power connections to the inside of the solenoid are made through electrically isolated vacuum penetrations.
- Ground loops are eliminated by using isolated power supply outputs.
- Safety ground is provided by station ground connections.
- To minimize delay and provide a fast crowbar trip, the SS is placed near the stations to control the trip.
- A straw drift-field voltage of 1.45 to 1.5 kV, with a maximum supplied current of 250 μA max is provided.
- The accuracy of the HV voltage is approximately 0.1 V
- The current readout is better than 10 nA at 250 μA max.

4.1. Measurement of Internal Capacitance

The capacitance per plane was estimated by applying 20 nA at 1450 V. The maximum stored energy was measured to be 0.21 Joule. This is below the required 0.25 Joule limit for systems operating over 400 V and with a resistance of 1 ohm. If a commercial HV supply is used, the discharge current adds less than 1.45 mA.

4.2. High Voltage Mother Board (HVMB)

Each panel has independent HV input, filtration, and crowbar systems.There are four connections to the HVMB.

- Low voltage output
- Ground
- Outputs from an Arduino board.

The SS are small (2 x 4”), and are instrumented to provide On-Off in individual channels with HV/LV isolation up to 2 KV, filtration, and crowbar if current limits are exceeded in a panel. Six SS, one for each panel, are instrumented per detector plane,

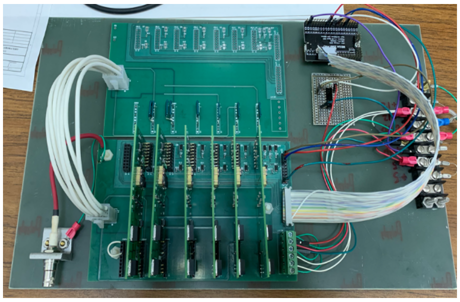

Figura 3: Mu2e High Voltage Mother Board (HVMB) containing 6 SS and one IV module.

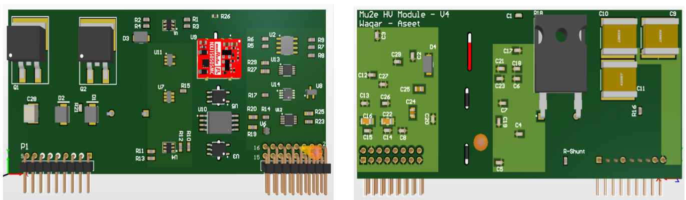

Figura 4: The smart Switch Board and crowbar circuit.

4.3. Smart Switch Board

In addition to the HV distribution, the Smart Switch (SS) also monitors current and voltage of each panel. The voltage monitor uses a (1000 to 1) voltage divider, and a current monitor using a shunt and an isolation amplifier. Figure 4 shows a Smart Switch board with a crowbar circuit. All SS boards are instrumented to provide individual on-off and have HV/LV isolation up to 2kV, filtration, and crowbar circuitry.

4.4. Crowbar

The Crowbar is designed to protect the system from HV discharge inside (or outside) a panel. The SS is equipped with a system-threat disconnect of the voltage when current in a panel exceeds a predetermined threshold (set by trip logic). The HV is routed through the SS where a current MOSFET (4) is used to remove stored energy in the HV distribution system within â2,5 msec to avoid repeated sparking. Two averaging cycles are completed in software for a trip response;
1) a 10-read average above a trip level,
2) a 100-read average for the current readout.
The measured response time of a trip is 2.5 ms.

To avoid noise in the long HV cables, there is a low pass filter for the HV input into the SS. This controls unavoidable spikes in the HV and reduces ripple-adding in the HV system. Low filtration hardware and a 250 msec average (software) in the isolation amplifier are both applied to control output variation, reducing the rms of the Voltage to 1 nA. The filter box also has a ground-break and a low-pass filter to reduce noise, providing a transition from coax to ribbon cable. There is a resistor in the RC low pass filter which acts as a diode bypass limiting the discharge through the crowbar. A Zener diode across the ground-break resistor is a safety measure to limit the maximum voltage on the ground shield of the ribbon cable which is connected to building ground.

4.5. Grounding

There are three grounding points in the system.

- The 1st floor racks, are required to be grounded for safety.
- A Detector Ground minimizes noise.
- A HV ground for each station. The tracking detector frame is electrically isolated from building ground.

Each station is electrically connected to Detector Ground. A single ground strap from each Station connects through a vacuum feed-through using the Instrumentation Feed-through Board (IFB) which penetrates the interior vacuum of the Detector Solenoid (DS). The IFB connects to the detector-ground bus. Four connectors are used for this purpose. Each connector accepts 4 Station-grounding straps. The 12 panels of each station have shared ground, but the stations are not directly interconnected. A HV ribbon cable separately connects each station to a shared ground. The SS has a low-pass filter which attenuates noise pick-up on the 6m length from the IFB to a station. A capacitor also provides a low impedance path to ground as required for the HV fuse to properly function.

4.6. Micro-controller Embedded Software

An Arduino (5) is used to monitor the current and activate the trip circuitry when an increasing discharge occurs in the planes As discussed in the above sections. The response time measured by the Arduino cycle time cycle is 250 msec. The Arduino acts as a software filter which provides 1000 current readings in the 250 msec. For a fast trip response, there are two averaging cycles in software. The first is a 10-read average to set the trip, and then a 100-read average when monitoring the current readout to obtain the 2.50 ms trip response. The Arduino also shares current data with the Raspberry-pi which controls the Bellinix HV supply through a serial terminal.

4.7. Raspberry Pi Communication

The Raspberry Pi (6) is a sub-system of the Bellinix power supply. It varies input voltage (1 to 5 V) using DAC controls and produces an output voltage of 1 to 2 KV. It also has a Reset and Clear line. The electronics racks in the data acquisition room are required to be grounded for safety and the Raspberry Pi interfaces, with 3 KV isolation, to the EPICS (7) control system and the Ethernet. It shares all parameters with EPICS input-output (IOC) commands.

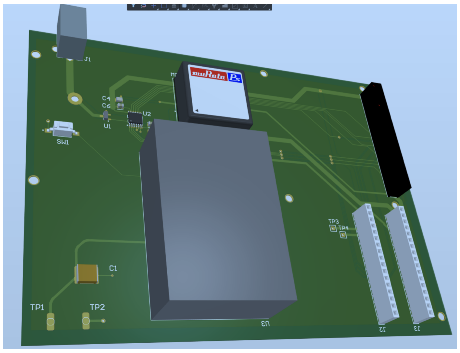

Figura 5: The Bellinx DC-DC power supply.

4.8. Bellinix High Voltage Power Supplies

Figure 5 shows the Bellinix High Voltage Power Supply (BHVPS) (8). It has a 12V input (isolated AC/DC) and uses a Raspberry Pi which has Ethernet connections. There is a 3 KV isolation. The Bellinix High Voltage Power Supply (BHVPS), DC-DC converters are used for input to the SS. These supplies are compact, have low noise, and can provide an output of 0-2 KV with a current of 2.5 mA. The output is set by a Digital to Analog Converter (DAC) with ≤ 5 % accuracy. The supplies are controlled using the Raspberry Pi. The HVDS design allows one supply per plane using jumpers between the 6 panels. If the jumpers are removed, the granularity could allow one HV source per panel.
The input of the Bellinix power supply is 12V with isolated AC/DC inputs. The entire system is installed on the HVMB in a 3U box.

5. HV Test and Validation

The HVDS was tested using procedures defined by Fermilab Safety Engineers and the Mu2e group (9). To test problems arising from unstable bean intensities, a beam pattern was generated using the Arduino controller simulating anticipated beam currents under various loads. The system was tested for 600 μA to simulate a resistive load equal to 6 panels and observing the response when switching the HV on and off which simulates a pulsed beam.

5.1. TABLE HV TEST

Table of HV Tests	
Test	Test Type
1	Voltage Ripple
2	Sag Under Load
3	Stability (1 week)
4	Ramp Characteristic
5	Magnetic Field
6	Load when Driving Long Cables

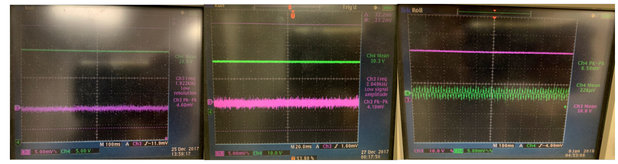

Figura 6: Ripple measured in three power supplies (left to right) without switching. 1.Wiener, 2.Bellinix, 3.Droege.

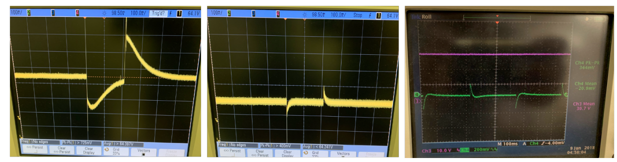

Figura 7: Ripple measured in three power supplies (left to right) 1.Wiener, 2.Bellinix, 3.Droege with switching.

5.2. Voltage Ripple

Voltage ripple is measured in milli-volts peak to peak (mV(p-p)) for most power supplies and instruments. This test is a measurement of the amplitude of the waveform in the HV as outlined in the 6 tests in the table below.

The Ripple measurement from highest to lowest values are tabulated using three power supplies and shown in Figure 6 for the 3 commercial supplies; (1) Wiener (10); (2) Bellinix (8); (3) Droege (11). Ripple was measured without switching the input supply voltage on/off for the three HV supplies. As shown in Figure 7; the Wiener supply measured 4.60 mV(p-to-p ; the Bellinix with the custom based design board measured 4.10 mV(p-to-p); and the Droege measured (8.50 mV(p-to-p).

5.3. Voltage Transition

To check the response voltage and currents, the three power supplies were tested by switching the input HV supply on-off using the SS to invoke the ON/OFF control in the Mosfet. As shown in the Figures the transition response of the HV power in the Bellinix and Droege supplies were found acceptable, The Wiener response did not meet requirements.

5.4. Voltage Stability

The voltage stability test was performed with and without load switching for a period of one week. The most important switching response was the beam profile when it was loaded with a 100 ft RG59 cable. All supplies meet the specifications set by Mu2e experiment. The variation of the voltage during switching was 20 mV.

5.5. Crowbar

Crowbar applies the intelligence of the SS which is used to shut down the HV in a panel if an over-current occurs. This is shown in Figure 8. The response-time of the crowbar was measured using the switching circuitry in the SS (0 to 2 to 0 kV).

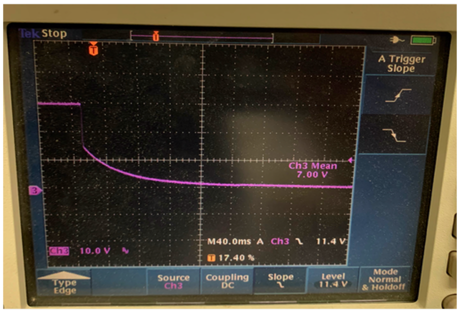

Figura 8: Crowbar response time using switching between 2Kv to 0.

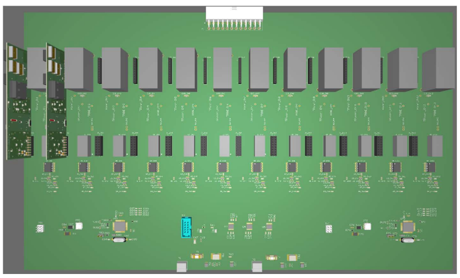

Figura 9: 12 channel stand alone 12 channel motherboard with smart switches for a straw station.

5.6. Magnetic field

The Bellinix, DC-DC power supply was tested in a 3 Gauss magnetic field at Fermilab. The system parameters were 2 KV at 200 μA. No change in the output of this power supply was observed.

5.7. Instrumentation Feed Through

PCB Instrumentation Feed through Board (IFP) and Printed Circuit Board (PCB), provide the structure for all electrical services. These boards were tested in vacuum and performed satisfactorily having an out-gas leak of 0,01 of the station leak-budget. For hardness, a test of 1.4 lbs stress was applied without significant change to a board. A HV test was applied for approximately one week at 2 kV in a 0.01 Torr vacuum to measure out-gassing. The results were satisfactory.

5.8. New HV Motherboard

After successfully tested a single DC-DC converter board with a de-multiplexer HV motherboard by using the Smart Switch. To increase the granularity of the Mu2e HV system we designed new 12 channels with 12 small DC-DC converters HV motherboard. As shown in Figure 9 the 1st version of the HV motherboard is under fabrication process.

6. Conclusion

In summary, this paper addressed the design and development of a high-efficiency HV distribution system which for each plane distributes and controls HV from a single HV input line into six output channels. It documents the development of an intelligent distribution control using a smart switch (SS) to provide voltage, crowbar and current monitoring. The applications of this system were tested under conditions expected in the Mu2e experiment. These tests included vacuum out-gassing in a 0.01 Torr vacuum, and the stability of the 2 kV high voltage distribution in a HV system with long cables, induced noise, and HV current switching. The application of a DC to DC converter was successfully demonstrated. The experimental results all show satisfactory performance.

7. Acknowledgement

The authors thank the US Department of Energy High Energy Physics for support of this research program. Dr Ahmed thanks H.Hoorani and A.Ahmad from National Centre for Physics Pakistan for providing the opportunity join the Mu2e program at FNAL through the University of Houston.

Referencias

[1] Mu2E Collaboration, Mu2e Docdb - Fermilab; Mu2e Conceptual Design Report; March 2012.
[2] CDR "The Mu2e technical design report, 2012."
[3] https://indico.cern.ch/event/121649/attachments/68416/98147/straw.pdfhttps://indico.c
[4] Mosfet High Voltage Current Breaker www.ech.ieee.org.
[5] http://www.arduino.ccwww.arduino.cc.
[6] Raspberry; rasberrypi.org/documentation.
[7] EPICS IOC Standards epics.anl.gov.
[8] www.bellinix.comwww.bellinix.com.
[9] IEEE Recommended Practices for Safety in High-Voltage and High-Power Testing, (in ANSI/IEEE Std 510-1983 , vol., no., pp.1-19, 1983, doi: 10.1109/IEEESTD.1983.81973).
[10] http://wiener-d.comwiener-d.com.
[11] Droege; "A new VME Based High Voltage Supply" ieeexploy.ieee.org - doc 25968.